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A DIRECT MEASUREMENT OF THE QUASI-PARTICLE TRAPPING EFFICIENCY FOR A NORMAL METAL TRAP

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We present preliminary measurements intended to directly probe the efficiency at which energy is transferred from quasiparticles in a large-area superconductor film to conduction electrons in a smaller, normal metal trap. Quasiparticle excitations are injected into a superconductor film by a normal-insulator-superconductor (NIS) tunnel junction. These excitations diffuse throughout the superconductor and are eventually trapped by an adjoining normal metal film. The power deposited in electrons in the trap is measured by a second NIS junction, where part of the metal trap forms the normal electrode. The efficiency of the trap is the ratio of absorbed to incident power. For an Al superconductor film and a Ag trap we measure a trapping efficiency of at least 10% near 100 mK.

1. Introduction

It has recently been recognized that quasiparticle trapping can be exploited to fabricate a new class of cryogenic detectors that are capable of collecting excitations over a large area, while simultaneously measuring the excitation energy using a much smaller sensor.[1] In this composite detector, excitations are absorbed by a superconductor film and subsequently break Cooper pairs to form quasiparticle excitations which diffuse throughout the superconductor and rapidly decay to the energy gap. An adjoining film having a lower gap can trap these quasiparticles and thus allow a measurement of either their number or total energy.

Recent advances in x-ray microcalorimeters have demonstrated that the current-voltage dependence of a normal-insulator-superconductor (NIS) tunnel junction can be used to measure the energy deposited in the normal metal electrode with unprecedented sensitivity.[2] The next generation of detectors incorporating large-area superconductor absorbers is thus likely to utilize normal metal traps. In what follows we present preliminary measurements intended to directly probe the efficiency at which energy is transferred from gap-edge quasiparticles in the superconductor to the conduction electrons in a normal metal trap. This trapping process will be efficient if quasiparticles relax by electron-electron interactions, and inefficient if the relaxation is controlled by phonon emission.

2. Experimental Approach

A schematic of the device used to measure trapping efficiency is shown in Fig.1. Quasiparticle excitations are injected into an Al superconductor strip via one of two NIS tunnel junctions. These excitations diffuse throughout the superconductor and are eventually trapped by an adjoining normal metal Ag film. The temperature rise of electrons in the trap is measured by a third NIS junction, where part of the metal trap forms the normal electrode. A superconductor electrode is used to make electrical but not thermal contact to the normal metal trap, thus allowing a known Joule power to be dissipated in the trap's electrons.

Ideally, the trapping efficiency is measured in the following way: a current I is passed through one of the injector junctions thus creating (I/e) quasiparticles per second. A given fraction α of these injected quasiparticles diffuse towards the trap, of which a fraction (1-β) recombine to form Cooper pairs before reaching the trap. The purpose of the second injector junction is to measure β. The net power dissipated by quasiparticles relaxing to the Fermi energy in the trap is

$$P_{qp}=\alpha\beta(I/e)\Delta. \qquad (1)$$

Here we have assumed that all of the injected quasiparticles have relaxed to the energy gap Δ of the superconductor before entering the trap.[3] The power which couples to the electrons P_e, is equal to the applied Joule power P_j, which raises the electron temperature in the trap by an amount equal to that caused by the injected current. The trapping efficiency is thus $\varepsilon = P_e/P_{qp}$.

3. Experimental Results

The device was initially tested by measuring the temperature dependence of the voltage across the thermometer junction for a fixed bias current which was chosen to maximize its sensitivity. Subsequently, a known Joule power P_j was dissipated in the normal trap and the rise in electron temperature was measured. We find that the dependence of electron temperature T_e on power is described by the following equation

$$P_j = \Sigma V(T_e^5 - T_p^5), \qquad (2)$$

where V is the volume of the metal, T_p is the lattice temperature, and Σ=4.4 nWμm^{-3}K^{-5}. This dependence is in good agreement with previously measured values for the coupling between electrons and phonons.[4] This result demonstrates that the thermal circuit is well understood and will also be used below in estimating the trapping efficiency.

In Fig. 2 we show the dependence of the electron temperature on the current I applied through the far junction. Also shown is the same dependence, but where the interface between the superconductor strip and the normal metal trap was physically scratched, electrically isolating the injector and readout circuits. Ideally, with the interface scratched, the electron temperature should not depend on the current I. In practice however, we find that power, probably dissipated in the resistance formed by the normal electrode of the injector junction, couples through the substrate into the normal metal trap,[5] thus causing the observed temperature rise. Consequently, part of the temperature rise observed for measurements of the unscratched interface is due to this additional channel for energy transfer. In future work, we intend to eliminate this channel by reducing the length and increasing the thickness of the normal electrode.

In order to estimate the trapping efficiency it is necessary to determine the net power P_e which couples to the electrons through the interface. This is done in the following manner: for each value of injector current I, both the electron and phonon temperatures are measured. The electron temperature is measured by the NIS junction in the usual manner for the unscratched case. The phonon temperature is equal to the temperature measured with the scratched interface because the electrons and phonons are in thermal equilibrium. The power P_e which coupled to the electrons is then determined from Eq. 2 using these measured values of T_e and T_p.

It is also necessary to evaluate the parameters α and β in Eq. 1 in order to estimate the trapping efficiency. The fraction α of injected quasiparticles which reach the normal metal trap is easily estimated from the diffusion equation, and is approximately 0.5 for the far junction. The fraction $(1-\beta)$ of quasiparticles which have recombined can be measured by passing a current I through the near injector junction and comparing with the signal resulting from the same current injected in the far junction. For the device described here, however, it was not possible to conduct this measurement.

In Fig. 3 we plot the dependence of $\varepsilon=P_e/P_{qp}$ on the current I injected through the far junction using $\alpha=0.5$, $\Delta=0.18$ meV to determine P_{qp}. Since recombination losses could not be estimated accurately for this sample, we artificially set $\beta=1$. For low bias currents the efficiency is approximately 17%, and decreases to 10% with increasing current. We conjecture that this decrease in ε arises from a reduction in the quasiparticle lifetime, and hence in β, as the current I is increased. If we assume that the injected quasiparticle population can be modeled as a thermal population having a higher effective temperature, then the general dependence of the trapping efficiency on bias current can be reproduced, using the theory of Kaplan *et al.* to calculate quasiparticle lifetimes.[3]

4. Conclusions

We have demonstrated that a normal metal film can trap quasiparticle excitations produced as far as 0.5 mm away from the trap in an adjoining superconductor film. The efficiency of this process is at least 10%. For the particular sample described here it was difficult to estimate the effects of quasiparticle recombination, although they are clearly observed. Consequently the value of the trapping fraction cited here should be taken as a lower bound on the true value. Future work will focus on measurements of recombination losses using the second junction and on reducing spurious heating effects, thus allowing a more accurate measurement of the trapping efficiency.

Acknowledgments

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References

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2. M. Nahum and John M. Martinis, Appl. Phys. Lett. 66 (1995) 3203.
3. S. B. Kaplan, C. C. Chi, D. N. Langenberg, J. J. Chang. S. Jafarey, and D. J. Scalapino, Phys. Rev. B 14 (1976) 4854.
4. F. C. Wellstood, C. Urbina, and J. Clarke, IEEE Trans. Magn. MAG-25 (1989) 1001.
5. We calculate that the thermal conductance through the Si substrate is about 100 times larger than through the superconductor strip.

Figure 1:

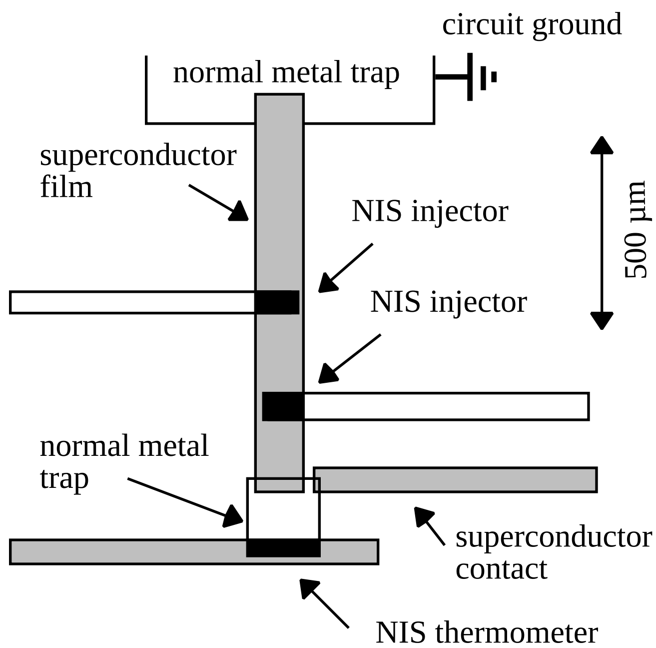

circuit ground
normal metal trap
superconductor film
NIS injector
500 μm
NIS injector
normal metal trap
superconductor contact
NIS thermometer

Figure 2:

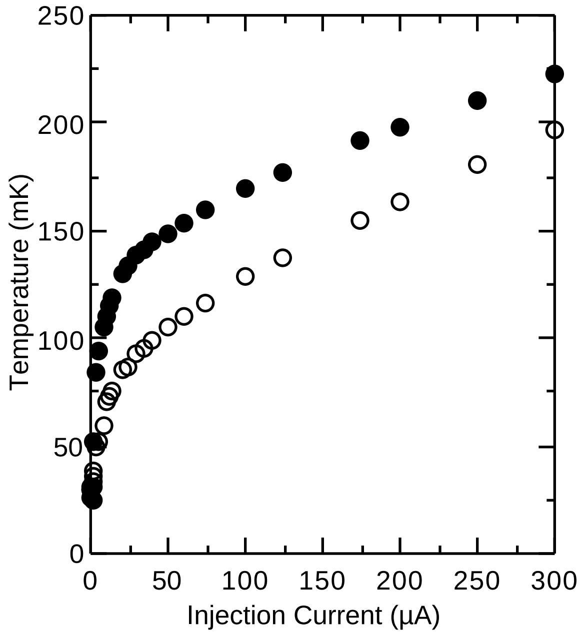
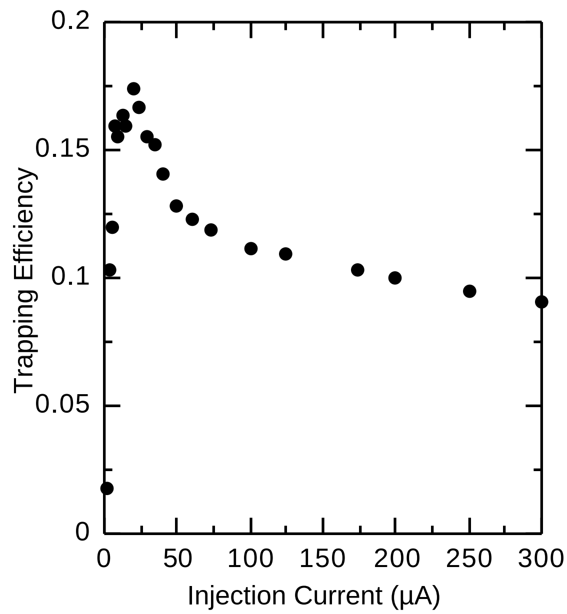

250
200
150
100
50
0
Temperature (mK)
0
50
100
150
200
250
300
Injection Current (µA)

Figure 3:



0.2
0.15
0.1
0.05
0
Trapping Efficiency
0
50
100
150
200
250
300
Injection Current (μA)

Figure Captions

Figure 1. Schematic of the device. Quasiparticles are injected into a 150 nm thick Al film via one of two NIS junction and are trapped by a 120 nm thick Ag film. An additional NIS junction is used to measure the temperature rise of electrons in the trap, and a superconductor contact is used to deposit a known Joule power in the trap. Hatched areas are Al superconductor regions, clear areas denote the Ag normal metal regions, and the darkened areas represent the tunnel junction. This device was fabricated using a micromachined Si evaporation mask and an electron-beam evaporator. The sample was fabricated without breaking vacuum.

Figure 2. Dependence of electron temperature T_e on the current I applied through the far junction. The filled circles are for an unscratched interface, the open circles are for a scratched interface, where the superconductor film and normal metal trap are electrically isolated.

Figure 3. Dependence of the trapping efficiency on the current through the far injector junction, not including a correction for recombination loss. We believe that the initial rise in efficiency is probably due to a small systematic error in estimating the electron temperature.